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FEASIBILITY STUDY ON THE USE OF A MICROWAVE SYSTEM FOR THE NONDESTRUCTIVE EVALUATION OF HISTORIC ADOBE STRUCTURES

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Abbreviations and Symbols

dBm	Signal level with respect to 1 mW, decibels
E	Electric field intensity, v/m
G_s	Average density of wall material
c	Velocity of light in free space, m/sec
e	Signal voltage
d_i	Sample or layer thickness, m
f	Frequency, Hz
i	0, 1, 2 for media 0, 1, and 2 respectively
R	Air path length, m
t	time, sec.
Γ	Reflection coefficient of a boundary
α_i	Attenuation constant, nepers/m
β_i	Phase constant, radians/m
γ_i	Propagation constant
ε	Permittivity, farad/m, where $\varepsilon = \varepsilon_i \varepsilon_0$
ε_i	Permittivity relative to free space (dielectric constant), farad/m
μ_i	Permeability relative to free space, henry/m
σ	Conductivity, mho/m
ω	Angular frequency, radians/sec
η	Intrinsic impedance, ohm

The subscript i is used in this paper to designate a special material to which the parameter applies. i = 0 is reserved for the free-space value of the parameter.

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Feasibility Study on the Use of a Microwave System for the Nondestructive Evaluation of Historic Adobe Structures

D. R. Belsher

A frequency-modulated continuous wave (FM-CW) radar system has been utilized at Tumacacori National Monument to provide usable on site information and to evaluate its potential for nondestructively measuring certain parameters associated with the soundness of historic adobe walls. The parameters of interest considered were layer thickness, presence, position, and thickness of voids or other inhomogeneities, and moisture content and its distribution. The results were generally favorable. The results indicate that an FM-CW system can nondestructively provide a major portion of the information needed to evaluate the soundness of adobe structures at a relatively low cost and in less time than present techniques. With some further work the FM-CW system can be developed into a useful archeological exploration and evaluation tool that should operate in rock and soils other than adobe.

Key Words: Adobe building materials; adobe soil; dielectric constant measurements; electromagnetic moisture measurements; nondestructive evaluation; radar soil measurements; soil moisture; underground radar; void detection.

1. Introduction

This work was carried out by the National Bureau of Standards (NBS) under a contract with the National Park Service, Department of the Interior (PX 8100 9 0003).

The preservation and restoration of historic adobe structures have become important in many parts of the world [1,2,3]. The preservation process for adobe structures is largely one of preventing deleterious effects of water, and the restoration process is often one of repairing water damage. For the safe and effective preservation of historic adobe structures, it quickly becomes necessary to evaluate the present condition of the structure.

To evaluate the existing condition of an adobe wall in a structure, it is desirable to know several things. Among these are the homogeneity, the extent and location of high moisture areas, and the thickness of plaster or other wall patching and covering materials.

An adobe wall may easily suffer voids and cracks due to water erosion that may not be fully visible at the surface. Voids can be generated by water entering the wall in an upper portion and following a porous path or a crack generated by the initial shrinkage of the adobe bricks or mortar and washing the adobe to a lower region of the wall. In the lower part of the wall, the adobe may merely be compacted by the settling of the washed material or the washed material may exit through a relatively small hole. Thus some voids or cracks may be quite hard to locate visually. The general homogeneity of an adobe wall can usually be assessed only by drilling holes at the present time. It is not desirable to drill any more holes than is absolutely necessary in an historic structure. In addition, those holes that are drilled may not detect an imperfection in the wall. A drill may easily miss a small but substantial crack lying in a plane approximately paralleling the hole. A thin porous area or a thin crack approximately perpendicular to the drilled hole may go unnoticed as drilling proceeds since only slight changes in resistance to the drilling may be evident.

Because high moisture areas of a wall can easily settle or fail from loss of strength, it is important to locate them and prevent moisture from entering [4,5]. Moisture can easily enter a wall from the ground by capillary action or from any leak in the roof

drainage system. It is not uncommon in some areas for adobe walls to be given a base of rock to inhibit the entrance of moisture by capillary action from the ground (fig. 1). At Tumacacori this rock barrier was sometimes only on the outer edges of the wall. Perhaps this was for splash protection of the wall.

An adobe wall may be covered or repaired with a mud, a lime and sand, or a cement plaster. Additionally, repairs may be made with concrete. Problems can arise from two sources when an adobe wall is covered with one of these materials. First, the covering material may be relatively impermeable and is then a barrier to the movement of moisture out of the wall. A previously stable wall area with low moisture content can become very wet with trapped moisture and subject to failure. Second, a layer of the covering material may have a gap in places where it was attached to the wall. In this case, failure of the covering material may be imminent but may not always be visually obvious. Also to facilitate maintenance or repair work it would be useful to know the thickness of these coverings and how the thickness varies over the wall.

A major goal of this work was to provide data that could be used during the preservation effort as well as for evaluation of the potential of an electromagnetic approach to obtain, nondestructively, information about the homogeneity, wet areas, and layer thickness of adobe walls.

For the field work a frequency-modulated continuous wave (FM-CW) radar was used in an attempt to obtain this information. Although other systems are available, this system was felt to have the most promise for field work of this type [6]. This type of electromagnetic system has been used mainly for measurement of aircraft altitude, and snow, coal and rock layer thickness.

Field work for this study was done at Tumacacori National Monument at Tumacacori, Santa Cruz County, Arizona. Data were taken using walls of the campo santo (cemetery), sanctuary (alter room), and nave (main assembly room) (see figs. 2, 3, and 4).

2. FM-CW Radar Description

The following equations outline the properties of a complex medium [7]. In general, waves propagating in a medium undergo attenuation and phase shift. For plane waves, the complex propagation constant in terms of the basic electrical parameters of a medium is:

$$\gamma = j\omega\left[\sqrt{\mu\varepsilon\left(1-j\,\frac{\sigma}{\omega\varepsilon}\right)}\right]^{1/2} , \tag{1}$$

and can be written as

$$\gamma = \alpha(\omega) + j\beta(\omega) , \tag{2}$$

where α is the attenuation constant and β is the phase constant. Solving for $\alpha(\omega)$ and $\beta(\omega)$ gives

$$\alpha(\omega) = \frac{\omega^2\mu\varepsilon}{2}\left[\left\{\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right\}\right]^{1/2} \tag{3}$$

$$\beta(\omega) = \frac{\omega^2 \mu\varepsilon}{2}\left[\left\{\sqrt{1 + \left(\frac{\sigma}{\omega\varepsilon}\right)^2} + 1\right\}\right]^{1/2} , \quad (4)$$

which for small losses ($\sigma/\omega\varepsilon << 1$) become, using a binomial expansion approach,

$$\alpha(\omega) \simeq \frac{\sigma}{2}\sqrt{\frac{\mu}{\varepsilon}} \quad (5)$$

$$\beta(\omega) \simeq \omega\sqrt{\mu\varepsilon} . \quad (6)$$

The intrinsic impedance of a medium is given by

$$\eta = \sqrt{\frac{\mu}{\varepsilon(1-j\frac{\sigma}{\omega\varepsilon})}} . \quad (7)$$

Initially, the adobe medium is assumed to be isotropic and homogeneous with parallel plane boundaries (see fig. 5). Electrical properties of any material can be described by permeability (μ), permittivity (ε), and conductivity (σ). The adobe is assumed to be nonmagnetic ($\mu = \mu_o$, where $\mu_o = 4\pi \times 10^{-7}$ H/m). Additionally, ε is assumed to be independent of frequency within the transmitted frequency band. Ray paths for electromagnetic energy are also assumed.

Due to the directivity of the ideal horns assumed in the model, only reflected waves are received. In practice, some control over the placement and polarization strategy are required to reduce the direct coupling to an acceptable level. The horns used were not ideal; however, a single-ray, normal-incidence model was used and provided useful results.

The reflection coefficient for any planar boundary can be written as

$$\Gamma = \frac{\sqrt{\dfrac{\mu_o\mu_2}{\varepsilon_o\varepsilon_2\left(1-j\dfrac{\sigma_2}{\omega\varepsilon_o\varepsilon_2}\right)}}\sec\theta_1 - \sqrt{\dfrac{\mu_o\mu_1}{\varepsilon_o\varepsilon_1\left(1-j\dfrac{\sigma_1}{\omega\varepsilon_o\varepsilon_1}\right)}}\sec\theta_o}{\sqrt{\dfrac{\mu_o\mu_2}{\varepsilon_o\varepsilon_2\left(1-j\dfrac{\sigma_2}{\omega\varepsilon_o\varepsilon_2}\right)}}\sec\theta_1 + \sqrt{\dfrac{\mu_o\mu_1}{\varepsilon_o\varepsilon_1\left(1-j\dfrac{\sigma_1}{\omega\varepsilon_o\varepsilon_1}\right)}}\sec\theta_o} , \quad (8)$$

for the case where the electric field is normal to the plane of incidence [8].

For the special case where the first medium is air, $\sigma_1 = 0$, where normal incidence is assumed such that $\theta_1 \simeq \theta_2 \simeq 0$, and where for the second medium, $\sigma_1/\omega_1\varepsilon<<1$ and $\mu_1 \simeq 1$, eq (8) becomes

$$\Gamma = \frac{\sqrt{\frac{1}{\varepsilon_2}} - \sqrt{\frac{1}{\varepsilon_1}}}{\sqrt{\frac{1}{\varepsilon_2}} + \sqrt{\frac{1}{\varepsilon_1}}} = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} . \quad (9)$$

In operation a microwave signal generator (see fig. 5) is swept in frequency over its bandwidth so that an output signal is produced that has a linear frequency change with respect to time. The microwave signal travels from the generator to the mixer by more than one path. If the electrical lengths of the paths were identical, the reference and test signals going into the mixer would arrive at the same time and the instantaneous rf frequencies would be identical at all times. But the signal that travels through the antennas arrives at a later time because that signal goes through the antennas and a path which may include the wall. A portion of the test signal is reflected at the near-side interface, and another portion is reflected at the far-side interface. These reflected signals arrive at the mixer at times t_2 and t_3, respectively, as shown above the mixer in figure 5.

Because all the reflected signals that are input to the mixer arrive at different times, the instantaneous microwave frequencies differ. The mixer is a product demodulator and has an output that is a function of the product of the inputs. Only the lowest difference frequency components in the output are preserved; the higher frequencies are filtered out.

The lower frequency components are displayed on a spectrum analyzer. The location of the first peak is a function of the distance from the antennas to the near-side surface. The location of the next peak is a function of that distance plus the wall thickness and its dielectric constant.

Assume for the moment that the microwave signal is incident upon an infinitely thick layer of adobe. Let the reference signal arriving at the mixer be represented as

$$e_1 = E_1 \cos \omega(t)t, \tag{10}$$

and the test signal reflected from the near-side surface be represented as

$$e_2 = \Gamma_1 E_2 \cos \left[\omega(t)\ (t + \frac{2R}{c})\right], \tag{11}$$

where 2R/c is the time required for the signal to travel a distance R from the transmitting antenna to the near-side surface and back to the receiving antenna. It is assumed that both antennas are equidistant from the wall surface and that the angle of incidence is zero degrees.

Going through the product demodulation process and neglecting the harmonic microwave frequency component, the mixer output signal is,

$$e_o \simeq \frac{\Gamma_1 E_1 E_2}{2} \cos \omega(t) \frac{2R}{c}, \tag{12}$$

where R is the distance from the antennas to the wall. Letting

$$\emptyset_{(t)} = \omega(t) \frac{2R}{c} = 2\pi f(t) \frac{2R}{c} \tag{13}$$

and

$$\frac{d\emptyset}{dt} = \frac{d\omega}{dt} \frac{2R}{c} = 2\pi \left(\frac{df(t)}{dt}\right) \frac{2R}{c}, \tag{13a}$$

the frequency of the signal out of the mixer is

$$f_{o1} = \frac{1}{2\pi} \frac{d\emptyset(t)}{dt}, \quad \text{or} \tag{14}$$

$$f_{o1} = \frac{2R}{c} \frac{df(t)}{dt} . \tag{15}$$

If the frequency of the microwave signal is changed at a constant rate, the frequency of the signal out of the mixer is proportional to the distance from the antennas to the near-side wall surface.

Extending the analysis to include a finite wall thickness bounded by the near-side wall surface and a far-side wall surface, the total received test signal is [9]

$$e_r = E_2 \left[\frac{\Gamma_1 + \Gamma_2 e^{-2\gamma d}}{1 + \Gamma_1 \Gamma_2 e^{-2\gamma d}} \right] e^{-j\omega(t)\ (t + \frac{2R}{c})} . \tag{16}$$

Recognizing that adobe is generally a lossy microwave material and utilizing typical relative dielectric constants of soil or adobe and air, the amplitude of the denominator in eq (16) is found to be approximately unity. Thus, neglecting the multiple reflection terms contributed by the higher order reflection term in the denominator, eq (16) can be written as

$$e_r \simeq \Gamma_1 E_2 \cos\left[\omega(t) \left(t + \frac{2R}{c}\right)\right] + \Gamma_2 E_3 \left\{\cos\left[\omega(t) \left(t + \frac{2R}{c} + \frac{2d\sqrt{\varepsilon}}{c}\right)\right]\right\} e^{-2\alpha d} . \tag{17}$$

Mixing this received signal with eq (10) will provide a mixer output signal

$$e_o \simeq \frac{\Gamma_1 E_1 E_2}{2} \cos\left[\omega(t) \frac{2R}{c}\right] + \frac{\Gamma_2 E_1 E_3}{2} \left\{\cos\left[\omega(t) \left(\frac{2R}{c} + \frac{2d\sqrt{\varepsilon}}{c}\right)\right]\right\} e^{-2\alpha d} \tag{18}$$

when the harmonic microwave signal is neglected.

The frequency of the first component is given by eq (15) and the frequency of the second component is given by

$$f_{02} = \left(\frac{2R}{c} + \frac{2d\sqrt{\varepsilon_2}}{c}\right) \frac{df(t)}{dt} . \tag{19}$$

The difference between eqs (19) and (15) is a frequency proportional to the thickness and the dielectric constant of the wall,

$$\Delta f_o = \frac{2d\sqrt{\varepsilon_i}}{c} \frac{df(t)}{dt} . \tag{20}$$

The procedure is to measure the dielectric constant, ε_i, on site and reduce the working equation to one unknown, d, the layer thickness or range,

$$d = \frac{c}{2\sqrt{\varepsilon_i}\ df(t)/dt}\ \Delta f_o . \tag{21}$$

The analysis given here for one layer may be extended for multiple layers [10,11].

3. Measurement Approach

Equation (20) of the previous section is a basic working relation for the FM-CW system.

The dielectric constant, ε_i, is a function of frequency for most materials. However, to use eq (20) with the FM-CW system, a constant value of the dielectric constant is assumed. For adobe walls, this value is usually and most easily measured by using eq (20). The output frequency difference between the responses of the front surface and the rear surface of a known thickness of adobe wall is measured, and this value is used to provide a value of dielectric constant, ε_i, for subsequent measurements. Usually the change in dielectric constant is small over the transmitted frequency range, and the resulting error in range, d, due to this source is negligible.

The dielectric constant can also be affected by changes in moisture content or density with respect to the wall area initially used to determine ε_i [12]. This means a measurement of the change in moisture content of a wall can be made as the surface is scanned. The dielectric constant can also be measured by using eq (9) and measuring a relative amplitude of reflection of the wall compared to a metal plate placed on the front surface of the wall. There are several common sources of error in this technique, but it is satisfactory for initial rough estimates of ε_i.

The effect on ε_i of changes in wall density may cause errors in range, d, if the change is very gradual. These errors can usually be detected and allowed for. If the density change is not very gradual or is random in a wall volume, scattering of the transmitted wave will result. The detection of voids or soft spots in the walls is dependent upon this.

To gain an idea of the sensitivity of the FM-CW system, note that eq (9) gives a reflection coefficient $\Gamma = 0.000624$, which corresponds to a return signal voltage loss of 64 dB, given a medium with a dielectric constant of 4.00 containing a boundary with a dielectric constant of 4.01. This should be within the dynamic range of an FM-CW system as used in this work. This change in dielectric constant corresponds to a density change in adobe of approximately 0.2 percent or a moisture change of about 0.1 percent [12,13].

The attenuation of an electromagnetic wave propagating through a material is described by eq (3). For adobe it can be assumed generally that the magnetic loss associated with μ will be negligible. Thus the observed loss will be due to the conductivity, σ, and the dielectric loss. It can be seen in eq (3) that the attenuation is frequency dependent and that by lowering the frequency of operation the loss of transmitted signal will be less for a given situation. It is important to choose a frequency band which is low enough to provide a reasonable amplitude of transmitted signal so that any reflections will be large enough to be detected.

The resolution is basically limited by the wavelength in the material being investigated. If one assumes an ideal FM-CW system and uses the Rayleigh criteria for resolution of the waveform on the spectrum analyzer, then the limiting size of a layer that is completely resolvable is [14]

$$\Delta d = \frac{c}{2\ df(t)\sqrt{\varepsilon_i}} , \tag{22}$$

where ε_i is the dielectric constant of the layer and Δd is the thickness of the layer. In practice, this limit is seldom achieved since the system is not ideal. It should be noted that a layer may be easily detected, but its thickness may not be resolvable. To gain resolution capability, the average frequency in the swept frequency band must be increased; at the same time, there is a competing requirement to lower the average frequency of the swept frequency band to increase range. It becomes necessary to make the best choice of these system parameters for an FM-CW system to be effective in a given situation.

4. Experimental Results

4.1 Campo Santo Wall

The west wall of the campo santo (cemetery) was chosen for the beginning work since it appeared visually homogeneous and moderately dry and access to both sides was relatively convenient (see fig. 6). This wall is located north and west of the church.

Initially, an FM-CW system operating at 2 to 4 gigahertz was used, but the excessive scattering due to the rough brick surfaces appeared to prevent a good response. A dielectric constant of $\varepsilon = 3.63$ and an approximate loss of 19.2 dB per meter were measured. At this time it was felt that a better response would be obtained from a system configured to operate at 1 to 2 GHz. This was tried, and the response was improved. Initial measurements gave a dielectric constant of $\varepsilon = 3.61$ and a loss of approximately 19.3 dB per meter. Due to the better response of the system using this frequency, the latter values were considered to be more accurate. Variations in dielectric constant measured along 3 meters of wall went from a low of 3.29 to a high of 4.10. Thus, if a central fixed value is assumed, a variation in range can be expected of approximately ± 6 percent due to this source. For the purpose of locating voids or cracks, this is an acceptable error.

A typical set of FM-CW responses along with a section of the campo santo wall is shown in figure 7. One curve shows the response directly over a niche approximately 29.8 cm deep on the back side of the campo santo wall. The second curve shows the response with the antennas moved 45 cm to the left where the wall is 58.2 cm thick. The peaks on the solid curve correspond to the front and back surface of the wall. The peaks on the dashed curve correspond to the front surface of the wall and the inner surface of the niche. The response shown in figure 7 shows a peak near the center that appears to result from a slight change in material parameters near the center of the wall. This appears to correspond to the mud mortar joint between bricks.

The resolution capability of an FM-CW system operating over the frequency range of 1 to 2 GHz is given by eq (22) as 15 cm for an air-filled layer. With this system operating from 1 to 2 GHz, a void must be approximately 15 cm in thickness before the thickness can be resolved accurately from the return signal. However, as shown in figure 7, detection (but not resolution) of a very thin void or boundary can easily be accomplished. To be detectable, a crack or void must have a component that lies at least partially in a plane approximately parallel to the wall surface. However, the voids lying perpendicular to the wall surface are much more likely to be seen by visual inspection. Thus the FM-CW system has a definite value in checking the homogeneity of adobe walls.

4.2 West Sanctuary (Chancel) Wall

When plaster or concrete overlay the adobe wall surface, it was not possible to resolve adequately the plaster thickness due to the frequency limitations of the available equipment. If the water content of the plaster or concrete is low, going to a larger bandwidth will probably give some usable results. In any case, it will be quite difficult to measure accurately a void thickness just behind the plaster. Although with an optimized system, the fact that a void exists may be noted. Since water has a loss of about 90 dB per meter at 1 GHz, the loss due to the moisture content of the wall material will quickly determine the usable frequency range and the resultant resolution possible from a reasonable system. Measurements were attempted in frequency ranges of 1 to 2 GHz, 2 to 4 GHz, and 8 to 12 GHz. Both the plaster and adobe had too great a loss for the 8 to 12 GHz system to give usable results. The 2 to 4 GHz system as configured with the available equipment lacked some sensitivity, and the results were not as good as with the 1 to 2 GHz system. Figure 8 shows an incompletely resolved plaster layer on the upper west wall of the sanctuary taken at position 2 (see figs. 3 and 4 for measurement location). Also shown in figure 8 are responses which appear to be mortar joints between brick courses and a return which originates with the outer wall surface. Since no borehole data are available for this location, it is assumed from the FM-CW returns that the wall is fairly solid. However, the combination of small responses on either side of the first, large, mud mortar joint return and the relatively large main return for this joint may indicate small cracks or soft spots on the sides of the mortar joint. These data were taken using a 1 to 2 GHz frequency band to get the best system results and reasonable penetration; thus, resolution is degraded from what may be possible with a higher frequency band. Total wall thickness was measured to be 0.95 m (37.5 inches) in this area.

Series 3 measurements were also run along the path shown in figure 9. These measurements were made at closely spaced intervals. They show local variations but are generally very similar to the sample measurement shown in figure 8.

4.3 West Nave Wall Areas

Several series of measurements on the west nave walls were made in the areas whose locations are shown in figure 3. Series 4 and 5 measurements were made as shown in figure 10. A sample measurement from series 4 is shown in figure 11. This graph shows some of the greatest inhomogeneities found in this area, but it is felt that the pertinent response peaks are not great enough in amplitude or width to suggest a serious flaw in the wall.

The series 4 measurements were made at 5.1-cm (2.0-inch) intervals going down the wall as shown in figure 10. A steadily decreasing, average dielectric constant was observed for the first 20 measurements. The values ranged from 7.4 at the top to 5.7 toward the bottom. In the absence of any observable changes in wall roughness, thickness, or density, it is assumed the moisture content is steadily decreasing over this vertical distance. Measurements made at NBS with sandy loam indicate that this change in dielectric constant corresponds roughly to a 3 percent change in moisture content [12,13]. This contrasts with the horizontal series 5 measurements that show extremely constant average dielectric constant values of about 6.7 for the complete distance.

In measurement series 5 there were some slight anomalous variations in response near the top of the window. These appeared to be associated with the upper wood supports for the window and were not considered notable.

Figure 11 represents results using a spectrum analyzer bandwidth of 15 hertz and shows the frequency spikes due to the repetition rate of the sweep frequency generator. Figure 7 represents results taken with a wider bandwidth on the spectrum analyzer and shows

considerable smoothing of these spikes and is perhaps easier to interpret visually. These figures represent different areas and are mentioned only to compare the output format which tends to be limited by the available equipment.

Also, series 6 measurements were made on the west nave wall as shown in figures 3 and 12. This was an area where a section of original plaster was pegged to the adobe wall with steel lag bolts to keep it from falling since the bond between the plaster and the adobe is failing. This series of measurements was directly opposite a vertical drainage canal on the outer wall. This canal area is about 0.5 meters wide and has a metal mesh under cement plaster which has been removed from adjacent wall areas. As a result of this, it would be expected that the outer wall response would be slightly enhanced in amplitude but also slightly spread out because responses from the canal area and the wall surface are at slightly different ranges.

The wall measured 1.7 meters (67 inches) thick, and the dielectric constant varied from 3.53 to 3.79 over this series of measurements. Comparing this to the other measurements implied the wall was relatively and consistently dry here.

As can be seen from the response shown in figure 13, the wall is quite homogeneous in this area. Also it can be seen that the plaster layer is not well resolved. Since the resolution of the front and rear surfaces of the plaster is not good, the first surface response contains the response of the back of the plaster as well as the response of the air to the adobe boundary if a gap exists behind the plaster. Thus the first surface response contains additional energy representing those areas where a gap exists, but the resultant difference in amplitude could only be significant under conditions where the wall surface topography and moisture are quite constant. Although a correlation exists between the first surface amplitudes of this series of measurements and the visually estimated gap behind the plaster, it is felt that it would be better to use an FM-CW system with antennas modified for this job and to operate at a wider bandwidth and somewhat higher frequency. If one is concerned about inhomogeneities in a wall of this thickness, it will be necessary to operate at a lower frequency and suffer some loss of potential resolution to get improved signal transmission to the far side of the wall and back.

The responses identified in figure 13 were originally correlated to the wall surfaces using reflecting metal plates while making other graphs of this series.

4.4 East Nave Wall

Series 7 measurements were made as shown in figure 14. The measurements were made 15.24 cm (6 in) apart in a vertical line that crosses a boundary between a new adobe replacement area and the original adobe. In figure 15 the relative amplitude of the surface reflection response is plotted with respect to the wall cross section. This amplitude corresponds roughly to the relative near-surface moisture content as taken from data provided by the National Park Service for the area of the old bricks. It does appear that this method will provide relative moisture values for the near surface. However, it is important to realize that the surface response amplitude is influenced by the surface roughness and conductivity of the material. In this case the area of new brick is relatively smooth, making the response slightly higher in this region than it would otherwise be. While the moisture content of the new natural soil adobe bricks was judged to be lower than the old brick at the surface at the time of these measurements, previously measured Park Service data showed them to be relatively wet. Just above the new brick the old bricks are relatively rough; however, the response goes up and then falls in a space of a few inches corresponding closely to the moisture content as taken from National Park Service data for the remainder of the measurements.

By going to a lower frequency range, the effect of surface roughness can be minimized so it is not a serious problem. These measurements were made using a frequency range of 1 to 2 GHz and could easily be made at lower frequencies where the variations in surface height are very small compared to a wavelength. In all these measurements, the surface roughness varied from quite smooth on some plaster surfaces to a value of about ± 2 cm for some of the roughest adobe walls.

The effect of conductivity (due to soluble salt content) can be appreciable, especially at lower frequencies. It is felt that this problem can best be handled by making a series of measurements in which the conductivities and the water contents are known to calibrate the system. This was not done in this study due to a lack of time.

Additional measurements were made in this area at position 8 to evaluate alternate antennas and to check on the average moisture content of the total thickness of wall. When the effect of any soluble salt was ignored, these transmission measurements gave a dielectric constant value of 4.62 that corresponds to an average moisture content of about 5 percent for a sandy loam [10]. This corresponds well to the Park Service estimate of the present value for this position. These last measurements were made using a metal plate to enhance the return signal from the outside wall. This extra effort could be avoided in most cases by operating at a lower frequency band. This method also requires a preliminary set of calibration data on a known thickness of wall before relative moisture measurements can be made, but should provide good results for the total relative wall moisture. These measurements can then be made when the search for voids is carried out.

5. Conclusions

A frequency modulated continuous wave (FM-CW) radar system has been utilized on site at Tumacacori National Monument to evaluate its potential for nondestructively measuring certain parameters associated with the soundness of historic adobe walls. At the same time, information was gathered to provide useful on site information. The parameters of interest considered were layer thickness, presence, position and thickness of voids or other inhomogeneities, and moisture content and its distribution. The results were generally favorable. It appears that an FM-CW system can nondestructively provide a major portion of the information needed to evaluate the soundness of adobe structures at a relatively low cost and in less time than present techniques when done in conjunction with a visual check.

During the field work, the ability to detect voids was demonstrated initially on the campo santo wall area. Here a niche approximately 30 cm by 40 cm by 20 cm deep was easily detected, and in addition the mud mortar joint in the center of the wall was detected (see sec. 4.1 and fig. 7). Although some inhomogeneities were found in many other spots, none were judged to be serious voids requiring immediate attention. The most notable internal inhomogeneity was found in the west sanctuary wall and is described in section 4.2 and shown in figure 8. The potential sensitivity of the system is quite good. As noted in section 3, the system can respond to a boundary difference in dielectric constant under reasonable conditions of 0.01. This sensitivity is usually degraded by increasing range, increasing electromagnetic loss (increasing water content), decreasing the size of the discontinuity as "seen" by the system, and increasing surface roughness of a boundary. These problems are all somewhat relative, and altering system operating parameters can commonly reduce their effects so that usable results are obtained. Based on these results, it is probable that an FM-CW system can be very useful for void detection.

The results of attempts to measure the thickness of wall covering materials (usually plaster) indicate some immediate success and that improved results can be expected by providing a system with greater bandwidth. As noted in section 3, given suitable operating parameters, the limit for complete resolution of two close signal returns from both sides of a layer can be described by eq (22). This relation shows that the resolution is essentially

a function of the bandwidth transmitted by the FM-CW system. Thus an improved system could be assembled to operate from 1 to 4 GHz. (System components are commercially available to cover this range but were not available for this work.) This should greatly improve the ability to measure the thickness of wall covering materials and to detect any voids behind them. In any case, an initial indication of completeness of the bond of the covering material to the adobe wall often may be obtained as described in section 4.3 and figure 13 and in section 4.2 and figure 8. This may be quite sufficient along with visual observation to effectively evaluate the status of a wall covering bond.

One of the most desirable pieces of information about adobe walls is the amount and distribution of any water contained in them. To obtain good values of absolute moisture in the general case will take an additional research effort, but the measurement of relative values of moisture can be effectively accomplished. These relative values can be converted to approximate absolute values by calibrating the system for a known set of conditions. That is, a preliminary set of measurements can be made on a given wall having known values of surface roughness and texture, soluble salt content, and moisture. Then, given similar walls, reasonable absolute values can be obtained.

For most work, relative values of moisture content will be sufficient and relatively easy to obtain. The average dielectric constant measurements can be directly correlated with the average moisture content if some reasonable assumptions are made [10]. The average density must be assumed to be constant, and the concentration of soluble salts in the moisture present must be assumed to be approximately constant. The dielectric constant can be obtained from the FM-CW returns using eq (20) as described in section 3.

The series 4 and 5 measurements described in section 4.3 give a set of dielectric constants that indicate the wall is wetter at the top and has a fairly constant moisture content in a horizontal direction over the distance covered. A transmission measurement was made at location 8 as described in section 4.4 to get an average total moisture estimate. Any sudden change in moisture content within the wall can be expected to give a reflection and thus be detected, although no changes were found on this site.

The FM-CW system can also be used as described in section 4.4 to plot changes in near-surface moisture content of adobe surfaces as was done at location 7. This can be done even though the range of the system might be insufficient to penetrate a wall or the back surface might be inaccessible. This requires essentially no computation and can be read in real time from the normal output of the system.

Another item which was considered was to use the FM-CW system to look for water table height. This was not done due to limited time, increased rainfall just prior to this work, and the belief that other methods might be more useful at this site. A stand pipe can be installed at most sites to provide continuously at least one good measurement point of water table position. Some work is being carried forward at NBS, Boulder, toward providing a high-frequency electromagnetic means of mapping water table positions as well as moisture gradients in the ground.

The value of an FM-CW radar system for evaluating adobe walls seems established. However, any further work to optimize the FM-CW system or to use it in the field would best serve all users if the data obtained could be tied closely to immediate and complete measurements of the soil type, amount and type of salts, moisture content, and void size and position. This information was not generally available for this work because of funding limits and the historical nature of the walls but would contribute greatly to future work. It would be desirable to pursue this work to develop accuracy limits for the moisture measurements and attempt to put absolute moisture measurements on a well-documented basis. Any future evaluation should also include the measurement of test walls carefully characterized and especially constructed for the purpose. These should include various

types and shapes of test inhomogeneities that can be accurately described and directly sampled.

Since layering, inhomogeneities, and voids are detectable in adobe walls, it seems reasonable that similar dectections can be made for adobe soils and other soils as well as rocks. As a consequence, it is felt that the FM-CW system should be compared to other archeological survey systems, such as the magnetometer, which are presently in use. The FM-CW system will respond to different parameters but can be expected to be very useful either as the primary survey instrument or as a secondary instrument used to provide additional information in selected areas. The FM-CW system can also be expected to provide information in volcanic soils, which often inhibit the effective operation of the magnetometer.

It is felt that the FM-CW system shows considerable promise as an archaeological analysis tool. It may, with some additional effort, be developed as an exploration and mapping tool to provide some unique capabilities.

6. Acknowledgments

The author wishes to thank Mr. Joseph Sewell and the staff at Tumacacori National Monument in addition to Mr. Anthony Crosby of the U.S. Park Service for their cooperation and assistance in this study. Also the extensive efforts, both in the field and in the laboratory, of Mr. Robert H. McLaughlin are greatly appreciated. The consultation and advice of Mr. Doyle A. Ellerbruch were especially helpful.

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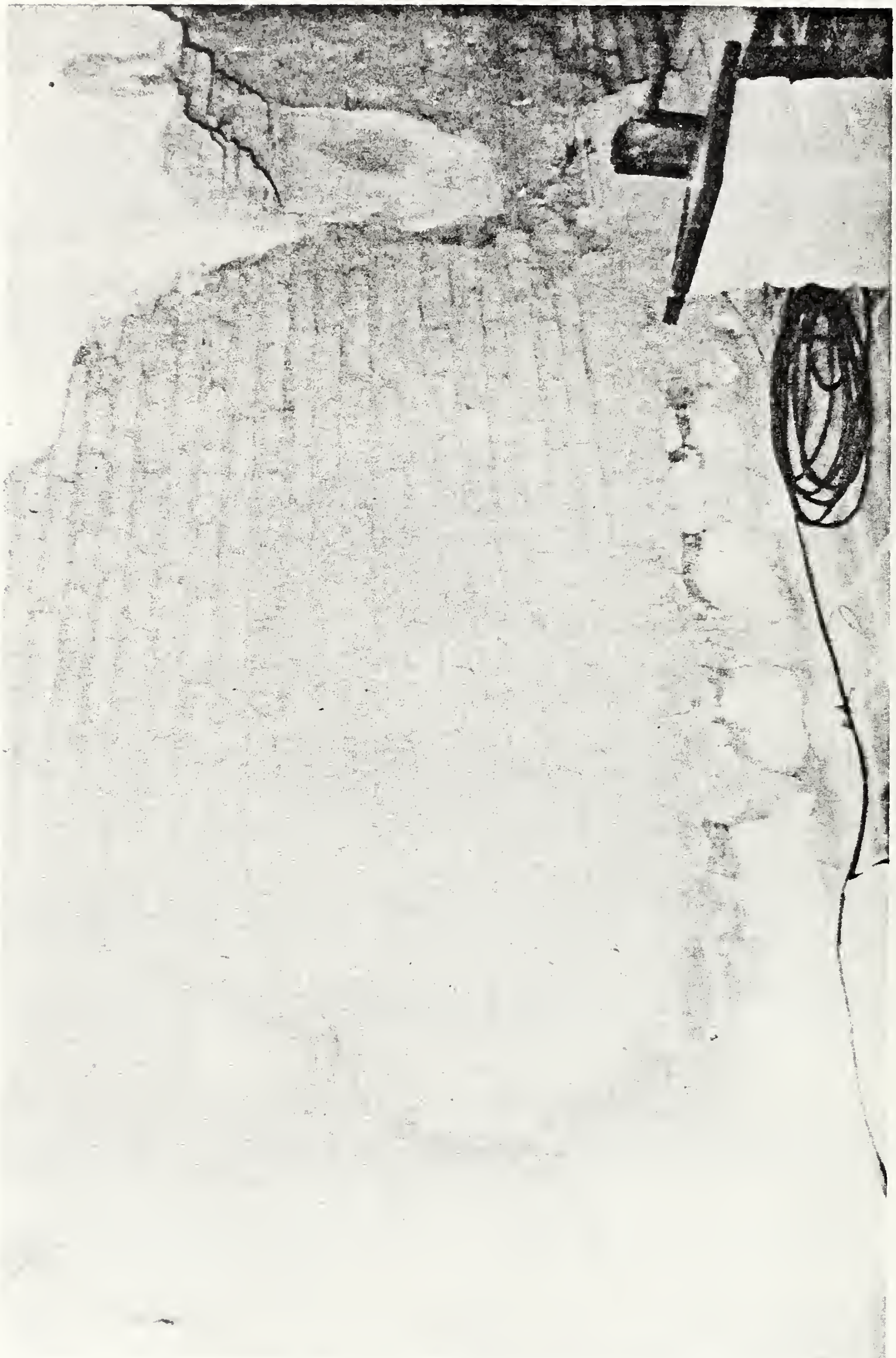

Figure 1. East interior nave wall showing rocks at the base.

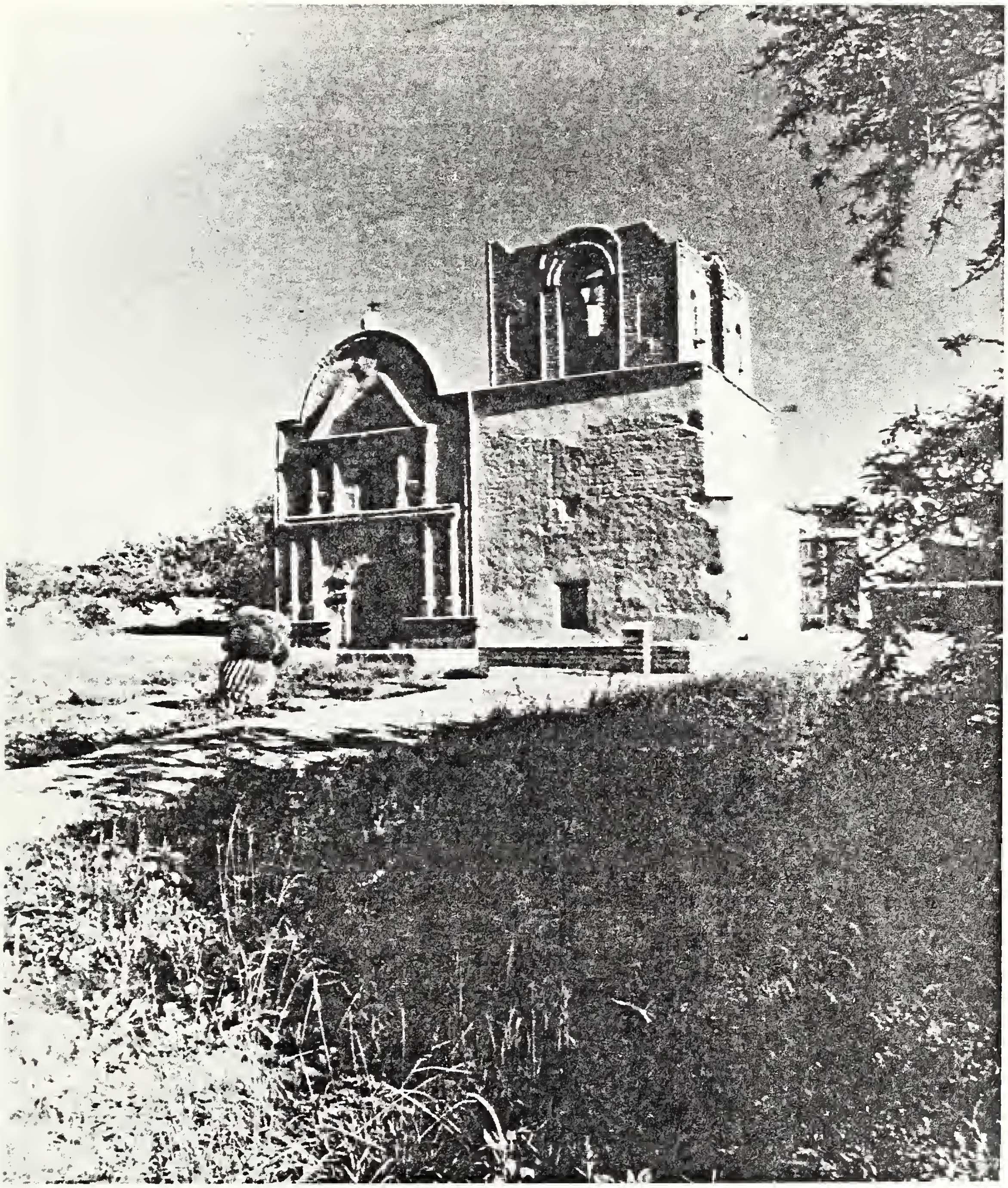

Figure 2. View of the church of San Jose de Tumacacori looking north. Photograph courtesy of the National Park Service, Department of the Interior.

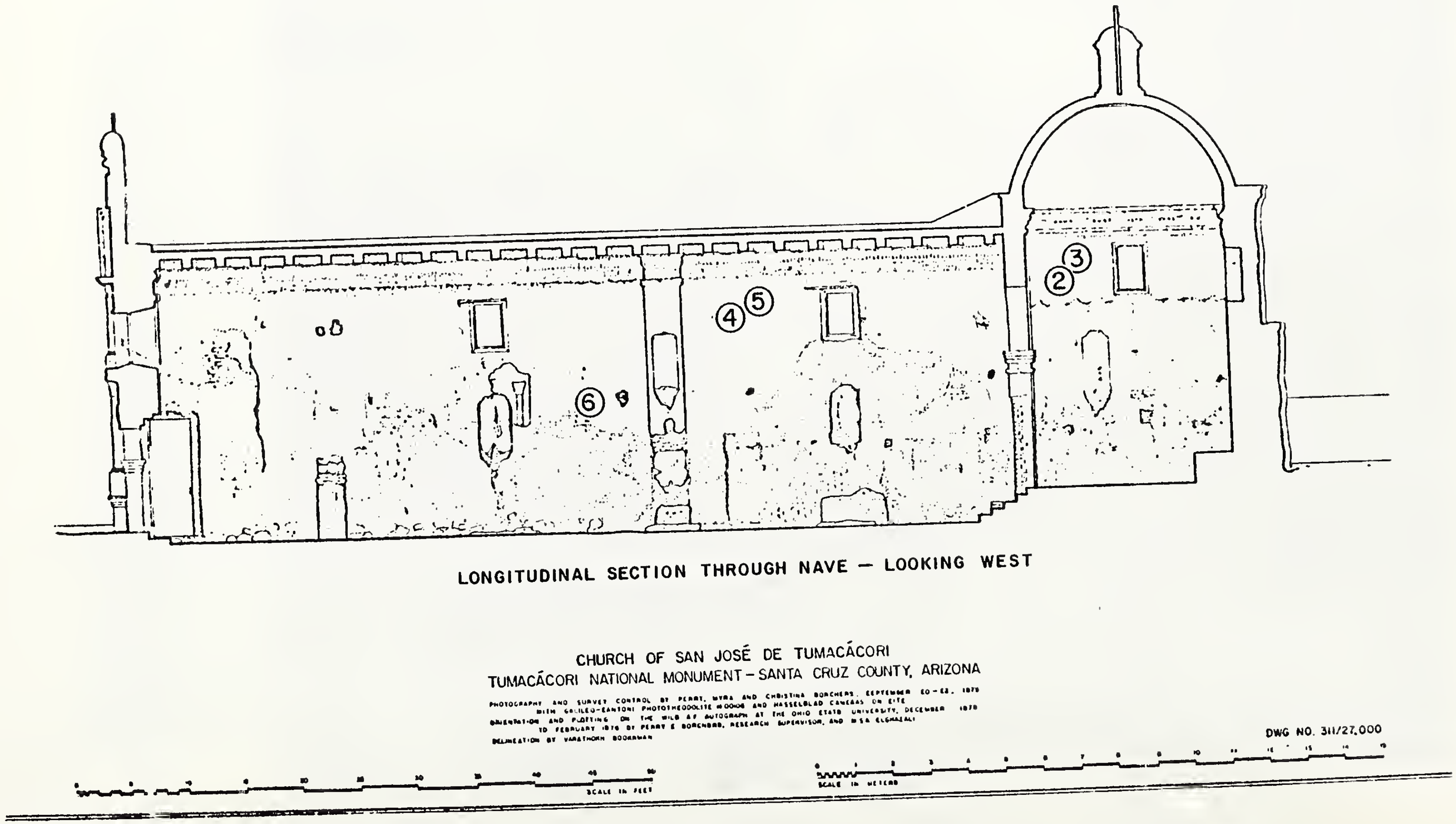

Figure 3. Interior view of west sanctuary and nave walls showing the general measurement locations by measurement number. Figure courtesy of the National Park Service, Department of the Interior.

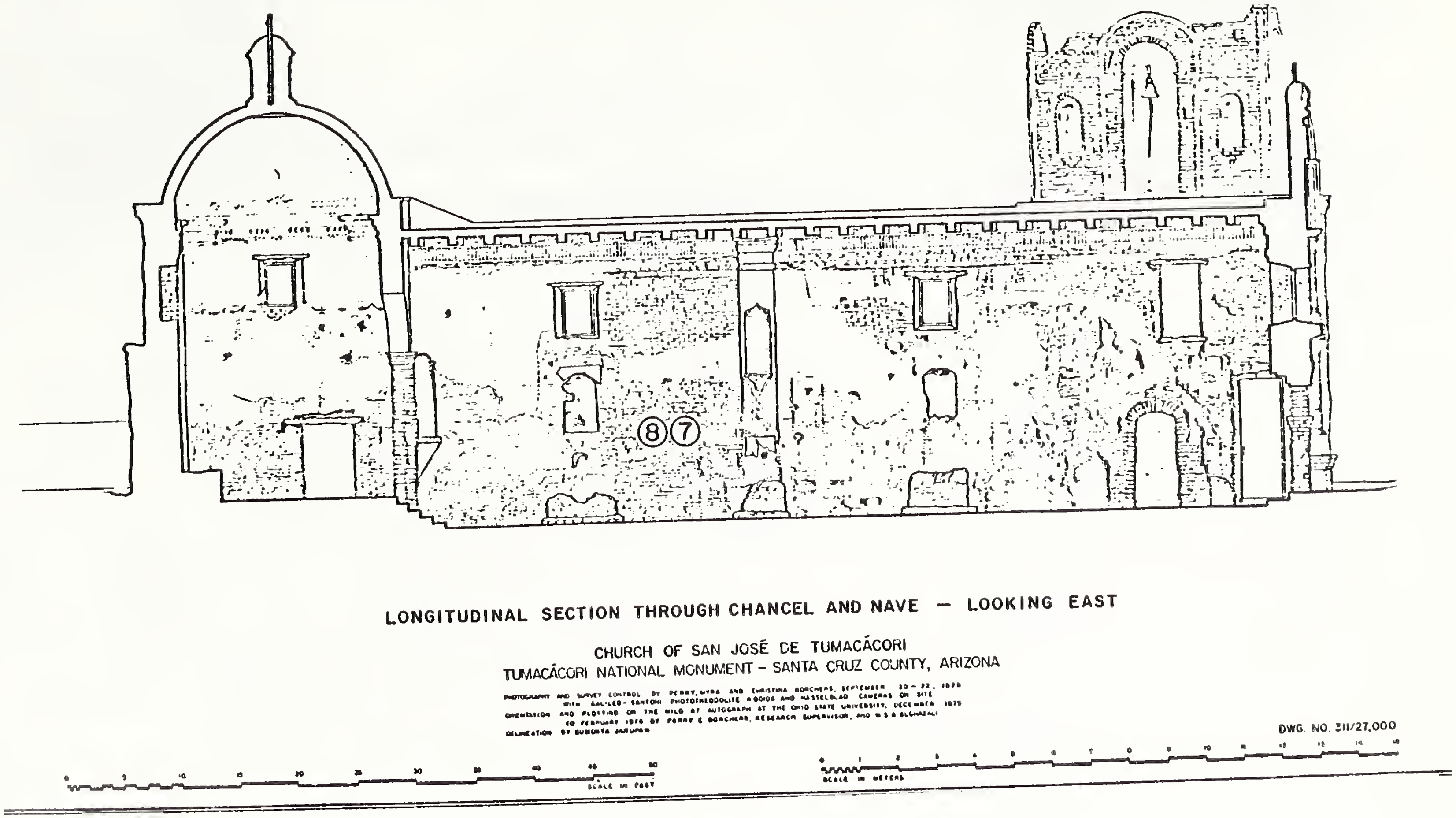

Figure 4. Interior view of the east sanctuary and nave walls showing the general measurement locations by measurement number. Figure courtesy of the National Park Service, Department of the Interior.

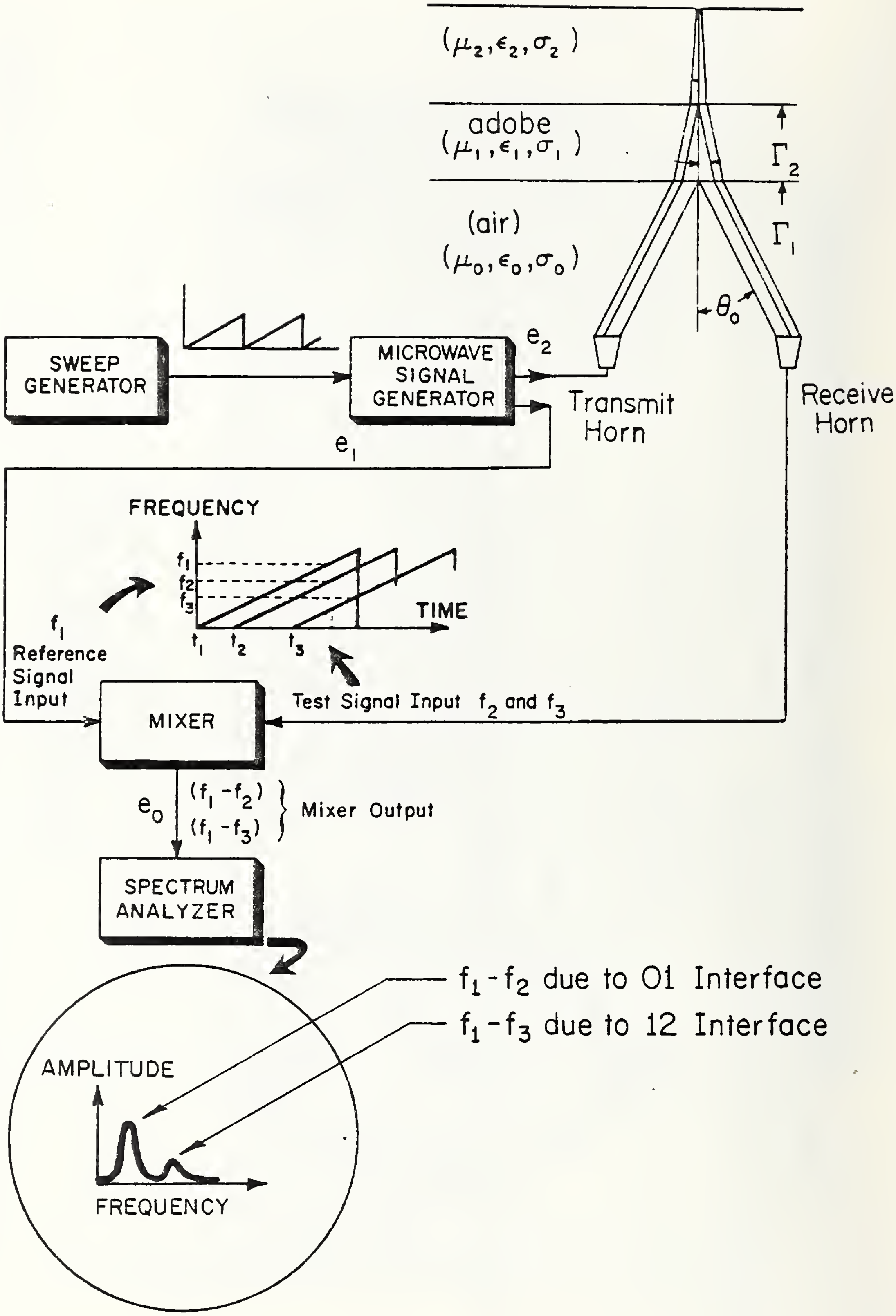

Figure 5. Block diagram of FM-CW electromagnetic system.

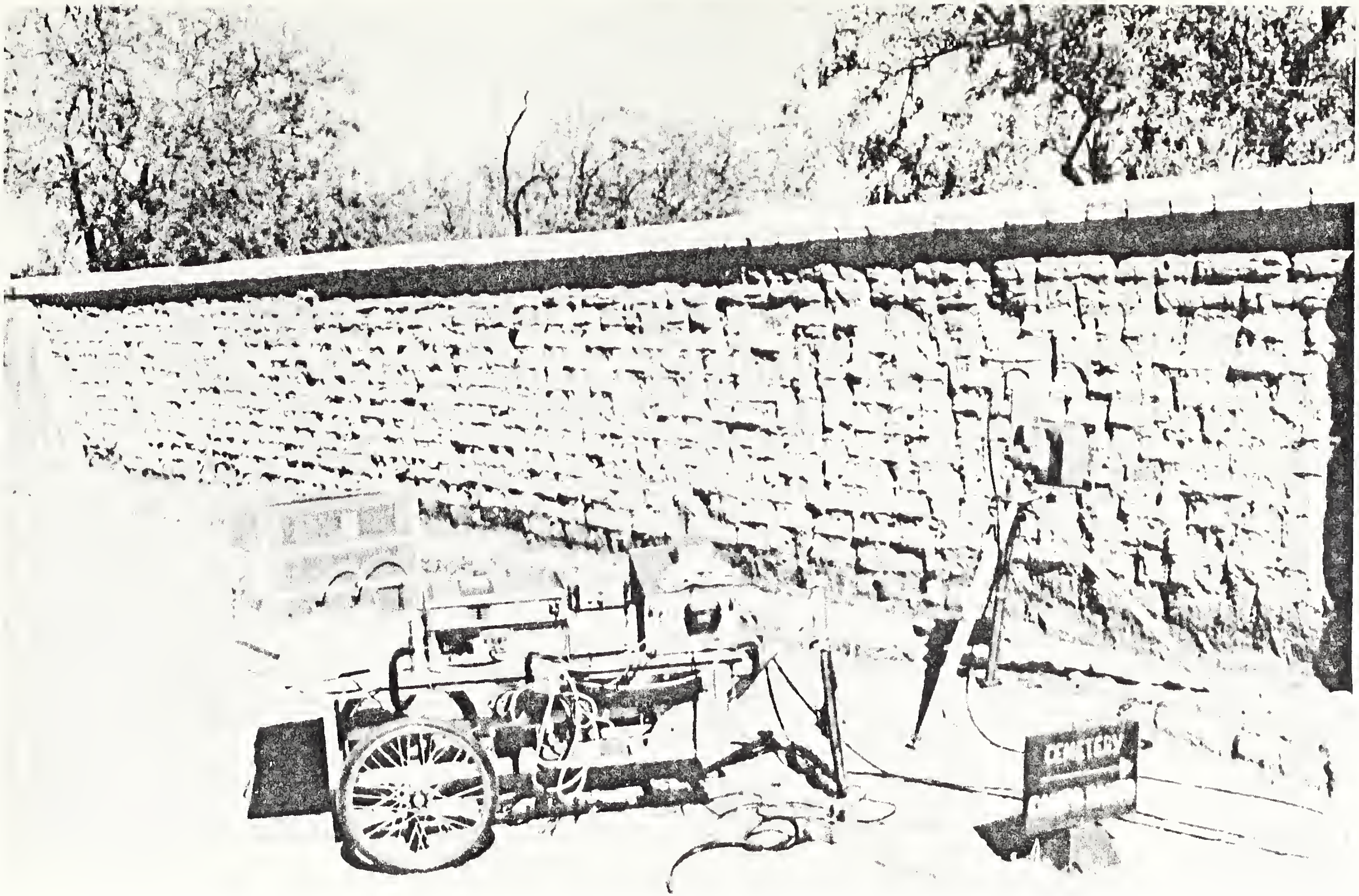

Figure 6. Camposanto wall site with test equipment.

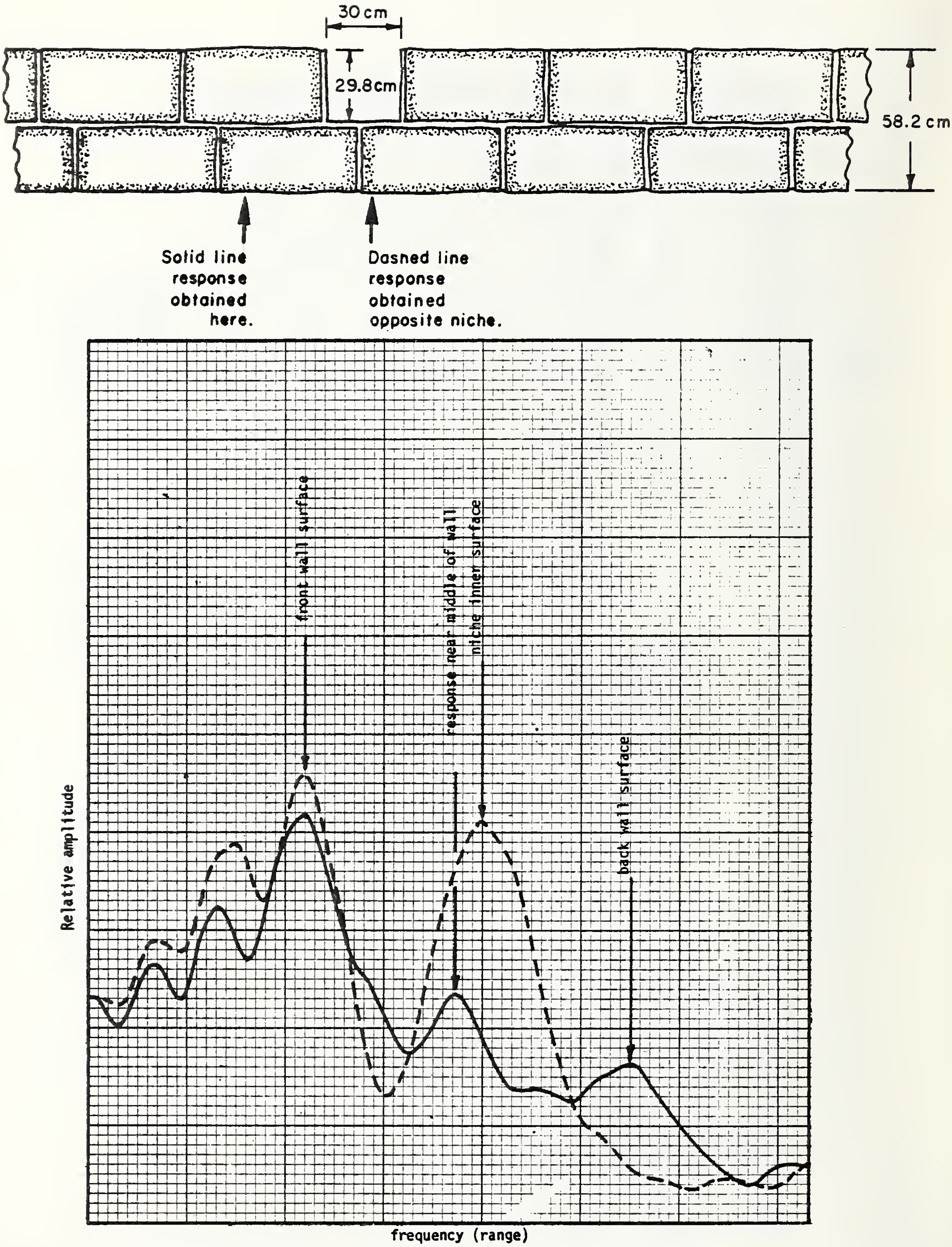

Figure 7. The FM-CW response of a solid area of the campo santo wall compared to the response obtained opposite a niche shown with the corresponding horizontal wall section.

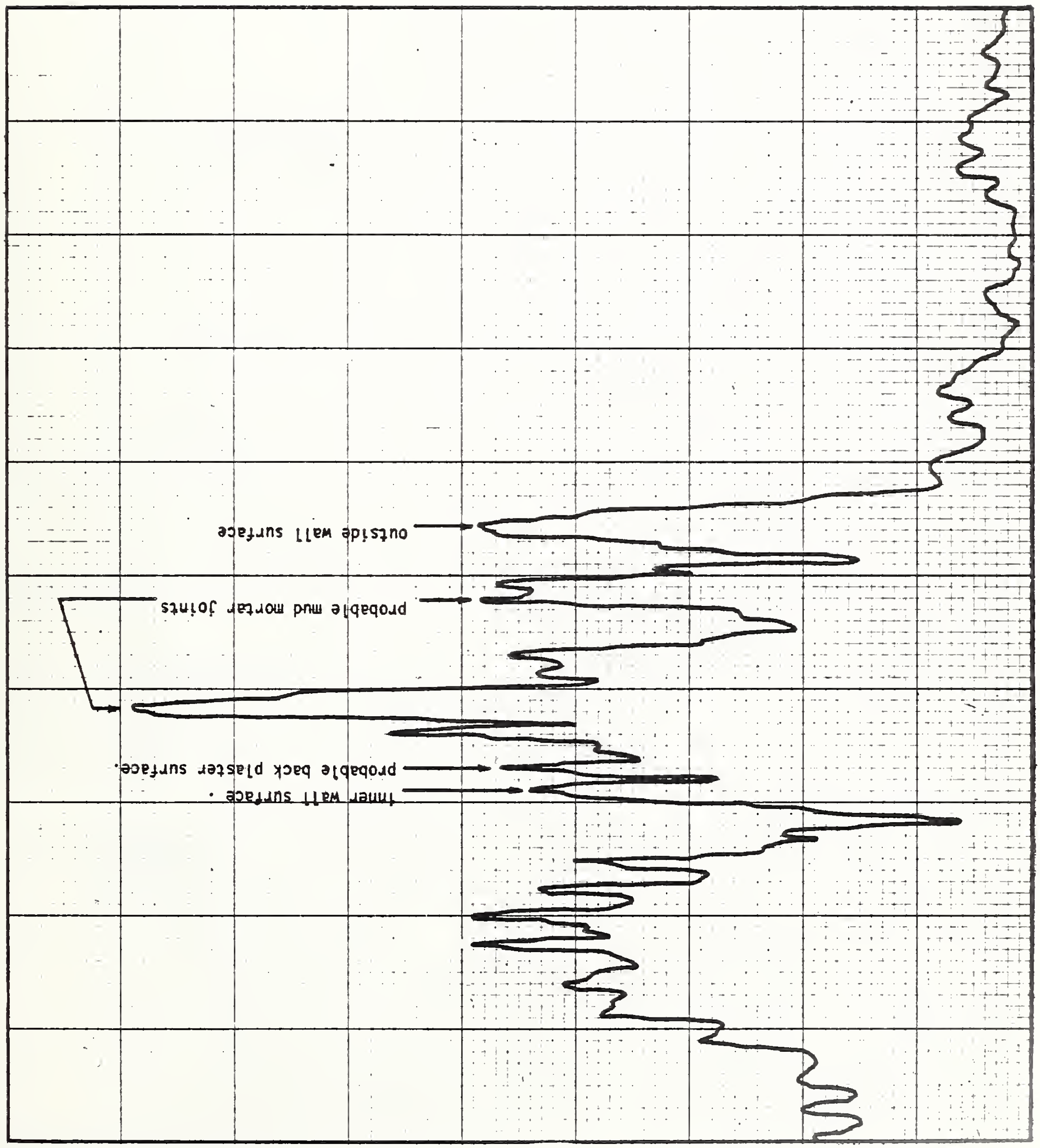

Figure 8. Response from upper west sanctuary wall.

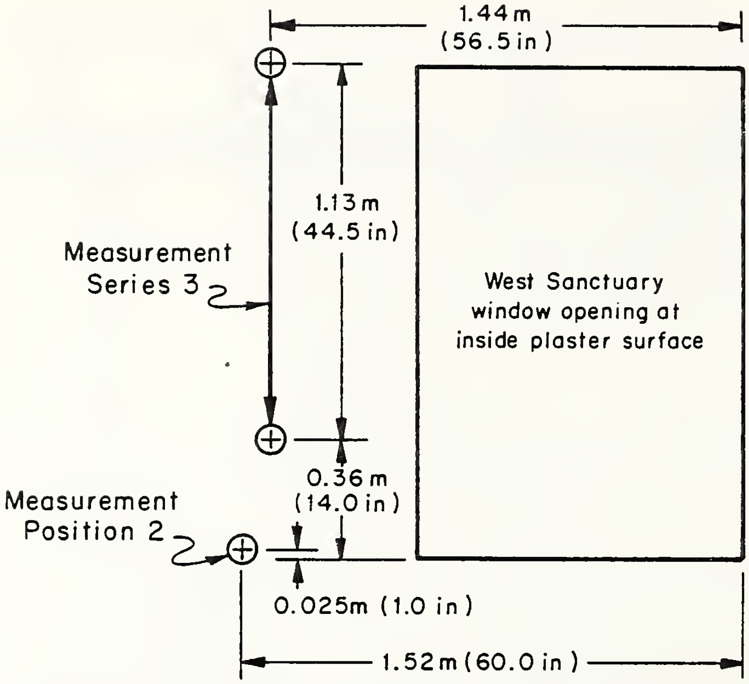

Figure 9. West sanctuary wall positions of measurement 2 and series 3.

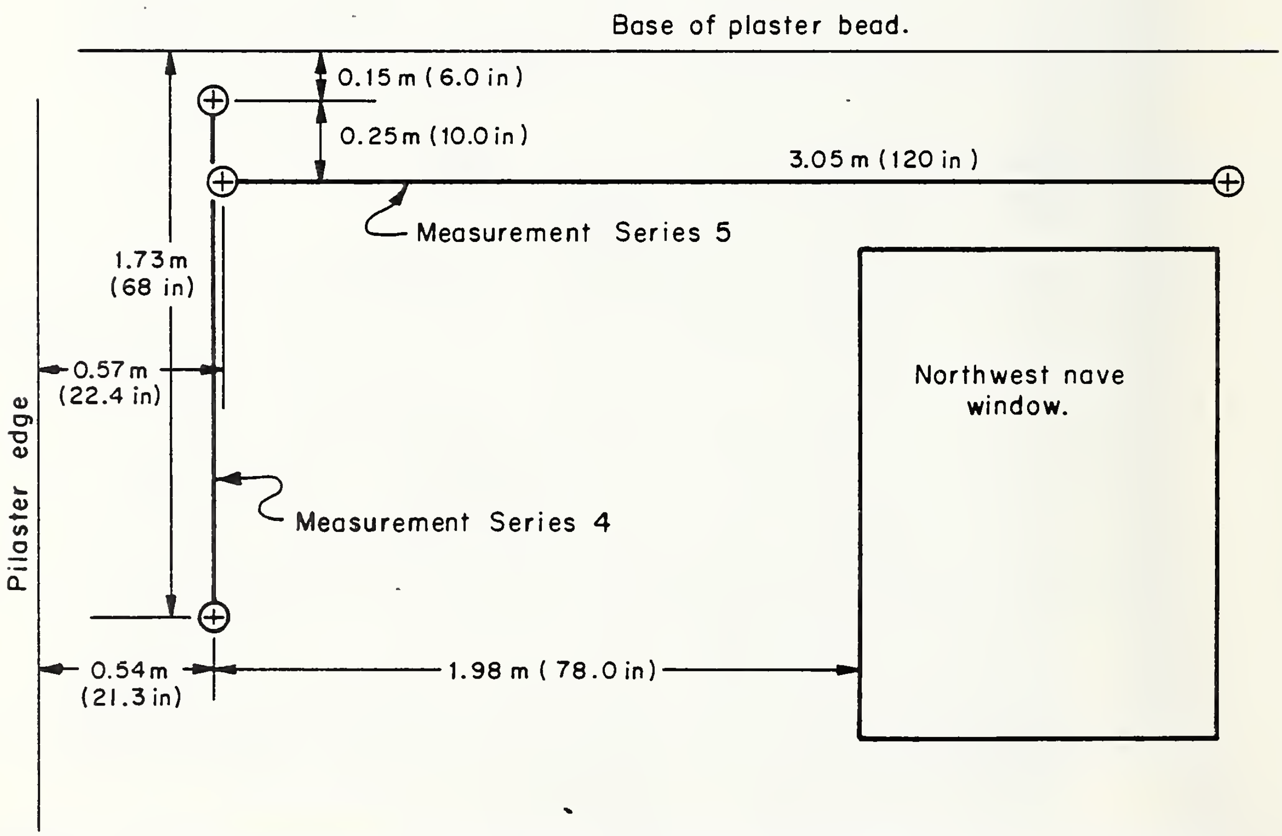

Figure 10. Northwest nave wall measurement positions of measurement series 4 and series 5. See figure 3 for the general location of these measurements.

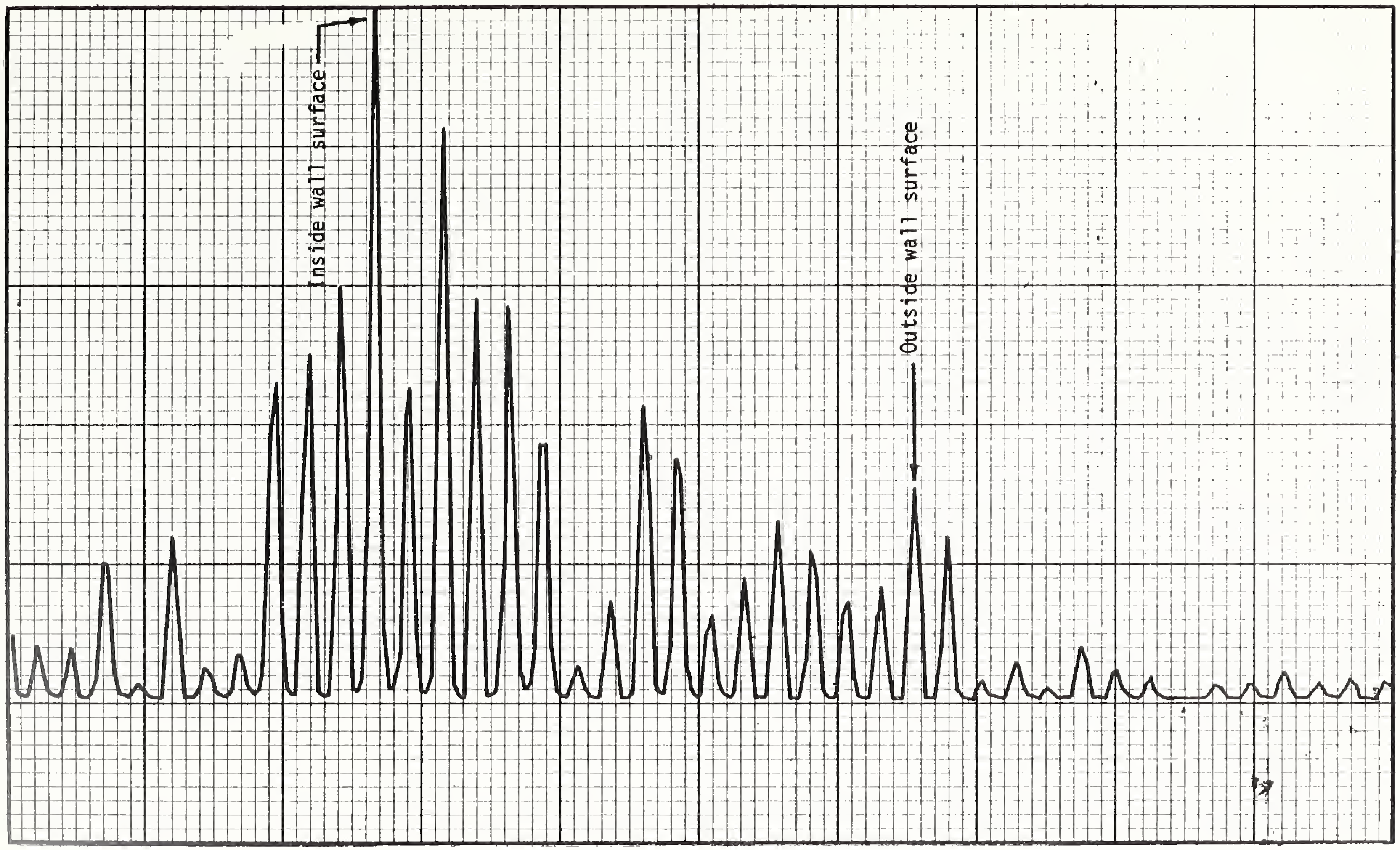

Figure 11. Response at 1.17 m (46 in.) down from bead in measurement series 4.

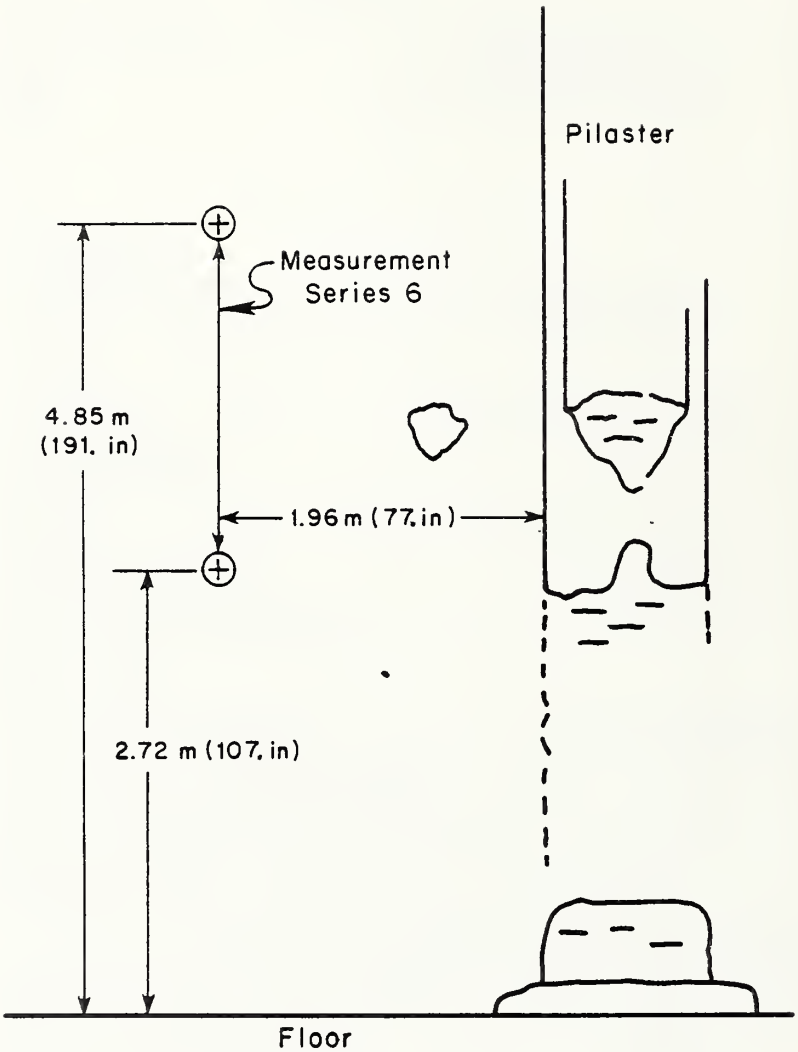

Figure 12. West nave wall position of measurement series 6. See figure 3 for the general location of measurement series 6.

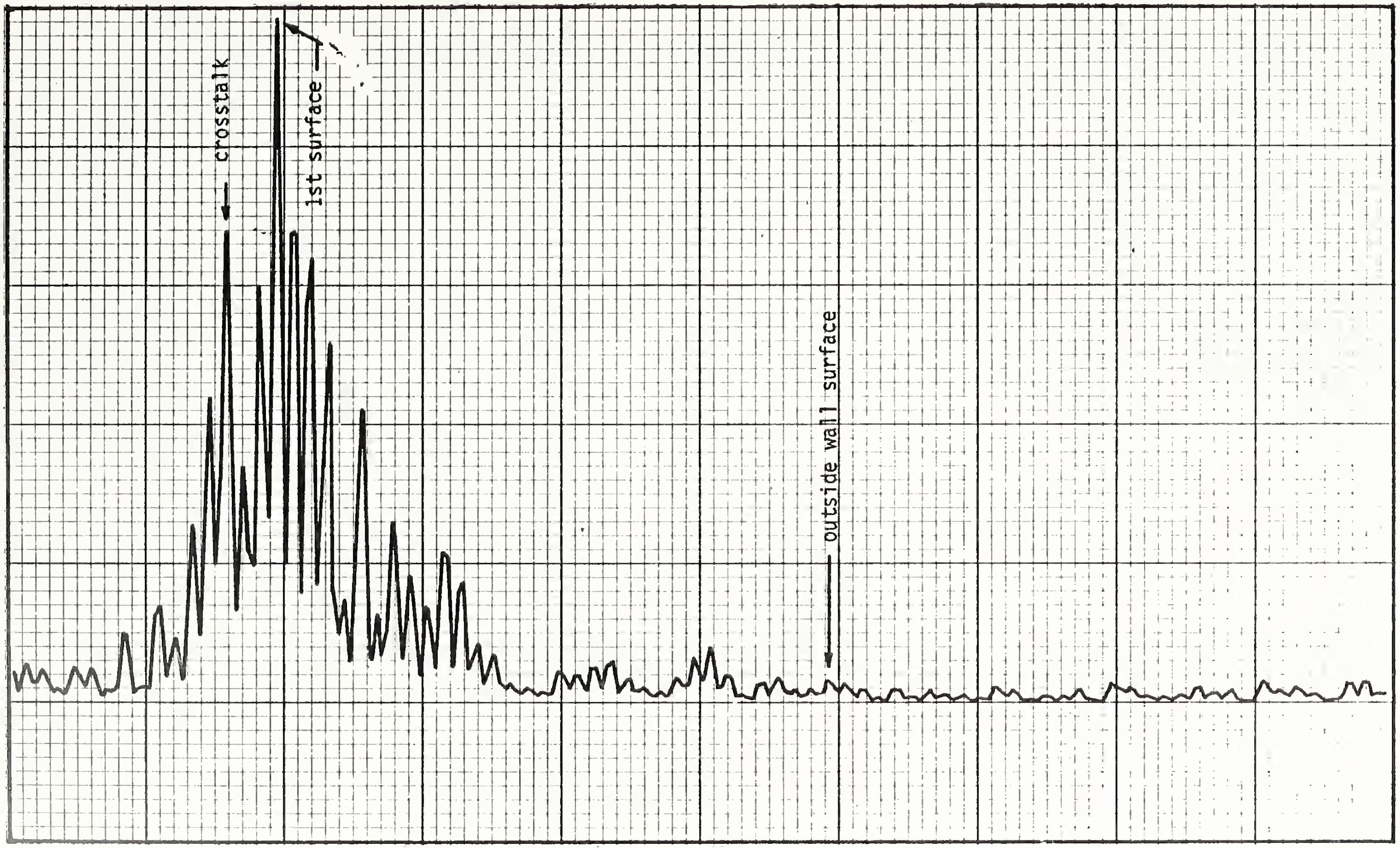

Figure 13. Response at top step in measurement series 7.

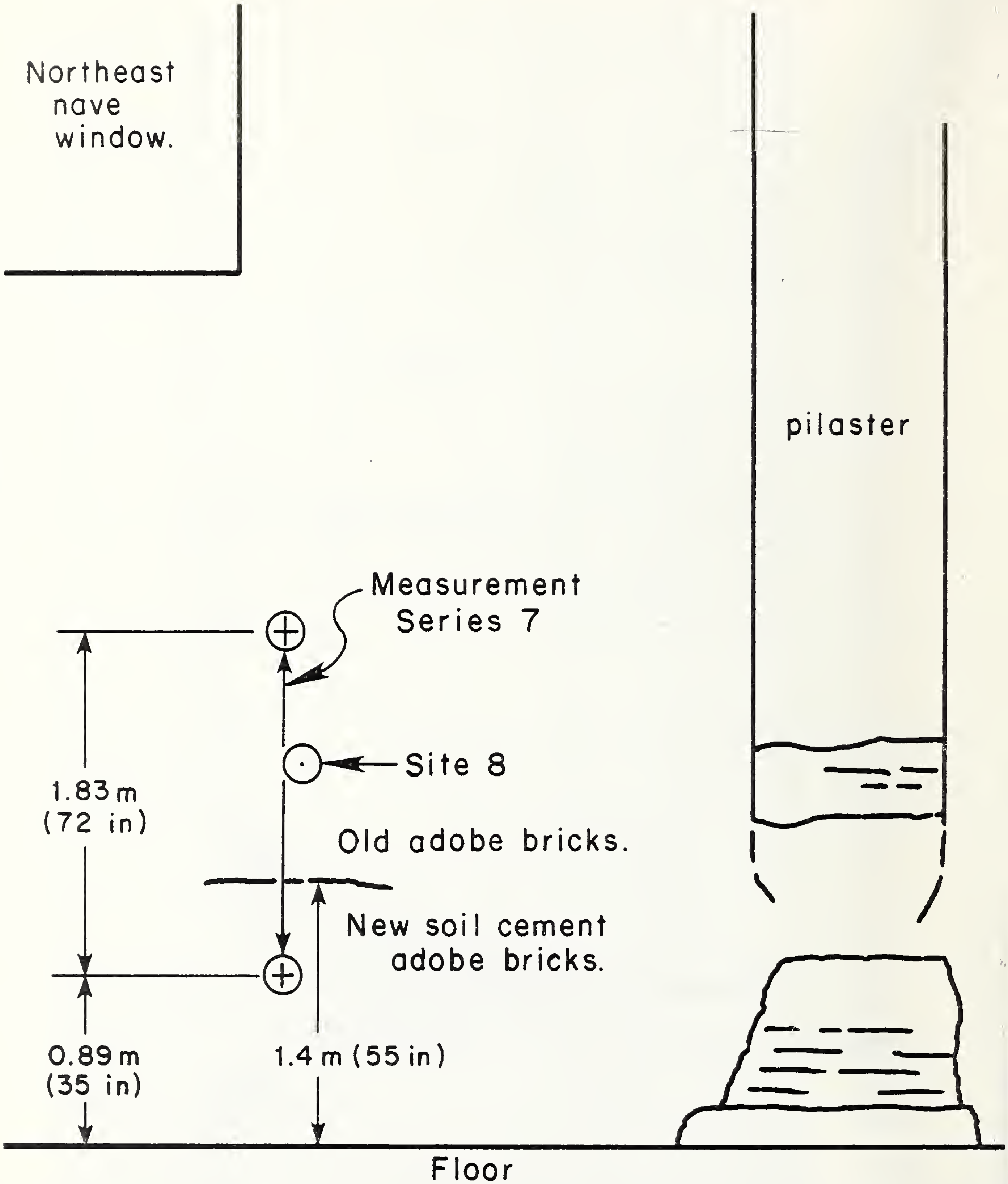

Figure 14. East nave wall position of measurement 8 and series 7. See figure 4 for the general location of measurement 8 and measurement series 7.

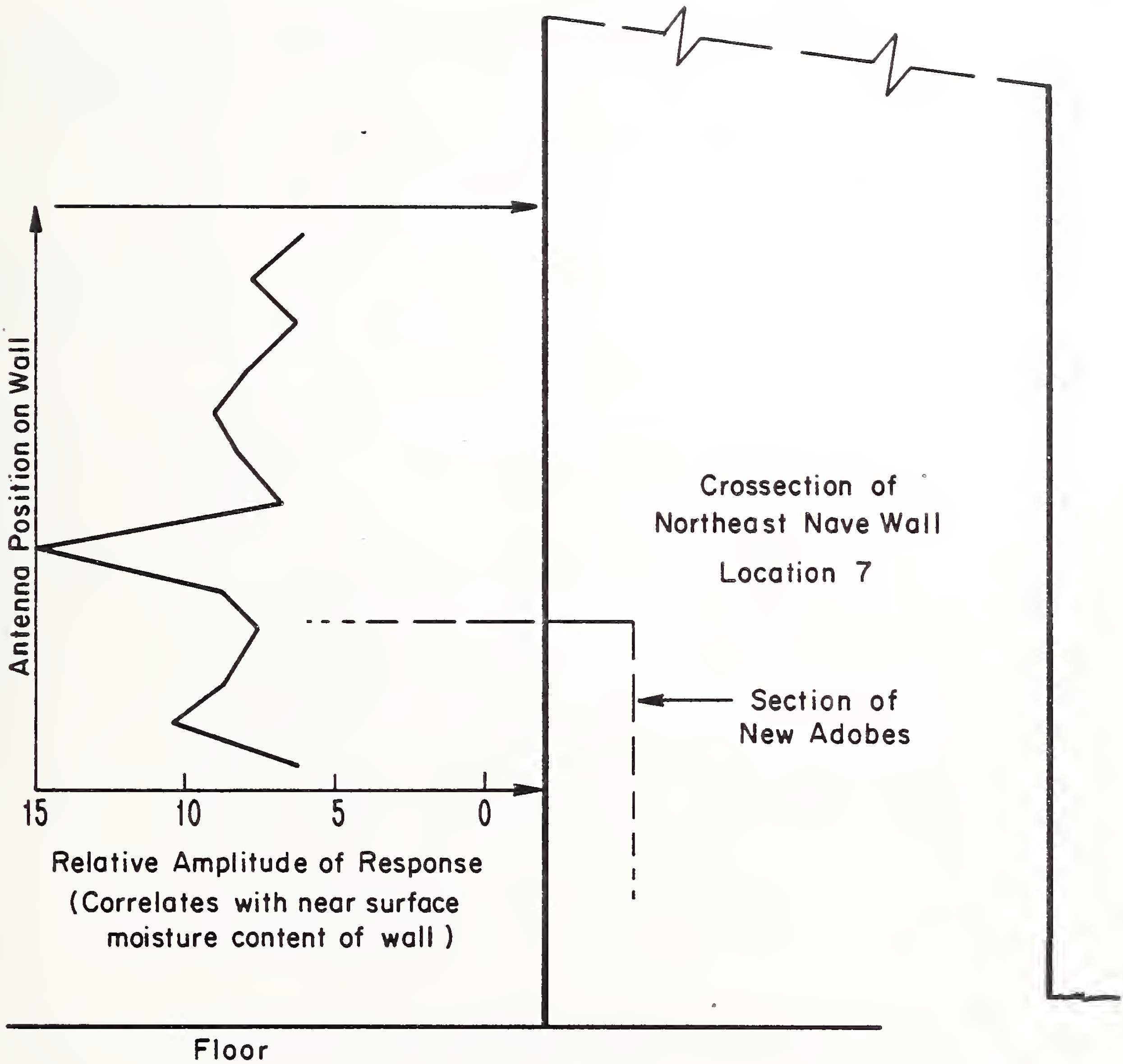

Figure 15. Cross section of the northeast nave wall at location 7. The amplitude of response of the FM-CW system is shown as it corresponds to the position of the antennas on the wall. As discussed in the text, the response amplitude correlates to the estimated relative near surface moisture.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A frequency-modulated continuous wave (FM-CW) radar system has been utilized at Tumacacori National Monument to provide usable on site information and to evaluate its potential for nondestructively measuring certain parameters associated with the soundness of historic adobe walls. The parameters of interest considered were layer thickness, presence, position, and thickness of voids or other inhomogeneities, and moisture content and its distribution. The results were generally favorable. The results indicate that an FM-CW system can nondestructively provide a major portion of the information needed to evaluate the soundness of adobe structures at a relatively low cost and in less time than present techniques. With some further work the FM-CW system can be developed into a useful archeological exploration and evaluation tool that should operate in rock and soils other than adobe.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Adobe building materials; adobe soil; dielectric constant measurements; electromagnetic moisture measurements; nondestructive evaluation; radar soil measurements; soil moisture; underground radar; void detection.

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